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The Carbon Footprint of Conventional and Organic Dairy Production: A Case Study of Two Portuguese Farms

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Abstract

To quantify the carbon footprint (CF) of dairy farms, numerous studies and calculators have been developed to determine greenhouse gas emissions. However, methodological variations across studies frequently lead to inconsistent or non-comparable results. This study evaluated the greenhouse gas emissions of dairy production using a two-farm case study design of two specific Portuguese dairy farms: a conventional intensive farm (Case A) and a pasture-based organic farm (Case B). The IPCC methodology was applied to estimate greenhouse gas emissions associated with ruminal fermentation, manure storage and nitrogen application to soils. The Rothamsted carbon model was used to estimate the amount of carbon sequestered in the soil of natural pastures on the organic farm. Our results show a carbon footprint of 1.43 kg of CO_2-eq/kg of energy-corrected milk (ECM) for the conventional farm and 2.82 kg of CO_2-eq/kg of ECM for the organic farm. When considering soil carbon sequestration in natural pastures, the CF of the organic farm was reduced to 2.06 kg of CO_2-eq/kg of ECM. Feed import was the largest source of emissions on the conventional farm, whereas ruminal fermentation was the largest source on the organic farm. Because this analysis is structured as a two-farm case study, the results represent the specific conditions of these two individual cases and are not generalize to conventional and organic dairy production systems as a whole. Nevertheless, this study constitutes a useful empirical baseline for identifying targeted greenhouse gas mitigation measures on these two farms—such as culling unproductive animals, adjusting diets, and improving effluent management—while highlighting the role of animal productivity in reducing emissions per liter of milk, as well as the impact of carbon sequestration in natural pastures on the carbon footprint.

Keywords: life cycle assessment; emissions; dairy cows; Portugal; carbon sequestration

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1. Introduction

Global greenhouse gas emissions were estimated at 59 Gt CO_2-eq in 2019, representing a 12% increase compared to 2010 and a 54% increase compared to 1990. The most recent report of the IPCC, in 2023, confirms a rise in average global temperature of 1.1 °C since pre-industrial levels. It projects a further increase to 1.5 °C during the decade of 2030 and shows the challenge in controlling the rise to 2.0 °C by the end of the century, with disastrous

impacts for the ecosystems and for human populations [1]. According to the Food and Agriculture Organization [2], the livestock sector accounts for 14.5% of global gas emissions. Of these, 41% originate from the beef industry and 20% come from the dairy sector.

The dairy sector releases three primary greenhouse gases to the atmosphere: methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) [2]. Methane, a prominent greenhouse gas in dairy farms, is mainly formed by a group of ruminal microorganisms belonging to the Archaea domain. These organisms reduce carbon dioxide using hydrogen to produce methane [3]. Nitrous oxide, a very potent greenhouse gas, is formed during the processes of nitrification and denitrification from nitrogen-rich sources, such as animal manure and fertilizers [4]. Carbon dioxide emissions derive primarily from electricity consumption and fossil fuel use during farm operations.

Over recent years, rising global demand for dairy products has driven production growth, resulting in a 15% increase in global dairy greenhouse gas emissions between 2005 and 2015 [2]. However, without concurrent improvements in productive efficiency, emissions would have risen by 38% over the same period [2]. In recent decades, European enteric methane emissions have declined, mainly due to shrinking herd sizes coupled with rising individual animal productivity, which has ensured food security [5].

There is a large range of mitigation measures which can be adopted in dairy farms to reduce greenhouse gas emissions. First, particularly in developing countries with low-productivity herds, total emissions per unit of product can be reduced by maximizing production and improving nutrition, health, and reproductive management [6]. Nutrition has a large impact on ruminal methane production. Diets rich in starch, balanced with adequate forage to support ruminal microbiota, favor the production of propionate in the rumen, leading to reduced methane production by methanogens. However, concentrate-rich diets are often criticized because they fail to utilize ruminants' capacity to convert fibrous, non-human-edible feed into high-value protein suitable for human consumption [7]. In recent years, feed additives such as macroalgae and 3-nitrooxypropanol have been researched for their methane-reducing potential [8]. On the other hand, greenhouse gas mitigation can be addressed through improved management practices. Those include genetic selection for more productive animals, effective reproductive management, increasing fertility and reducing the number of non-productive animals. Enhancing the health and welfare of the animals also leads to optimal efficiency and productivity [9]. Furthermore, soils have a significant capacity for carbon retention. Promoting practices that enhance this ability, such as no-till farming, the use of cover crops, rotational grazing, or the addition of materials like biochar, helps remove carbon dioxide from the atmosphere and improve soil health [10].

Organic production is often promoted as a more environmentally sustainable alternative to conventional agriculture, which is associated with higher emission of greenhouse gases, greater soil erosion and acidification, and water contamination and eutrophication [11]. However, while organic agriculture has a smaller impact per unit of area, its impact per unit of product can be higher due to lower yields [12].

In recent years, numerous studies have emerged with the aim of estimating the CF associated with dairy production. However, analyses based on benchmark farms often fail to capture the complexity and variability of individual farms, making it challenging to tailor mitigation strategies. Additionally, studies often exhibit inconsistent methodologies, which complicates inter-farm comparisons. The CF quantifies the emissions of greenhouse gases during the production of dairy products [13]. This article aims to evaluate the CF of two Portuguese dairy farms using a two-farm case design. We aim to quantify the primary emission sources within each farm. We thereby expect to determine emissions of CH_4 from ruminal fermentation of cows, CO_2 from farm activities and N_2O from manure and synthetic fertilizers. Direct emissions of N_2O are considered, as well as indirect emissions,

from nitrogen that volatilizes into the atmosphere in the form of ammonia (NH_3) and nitrogen oxides (NOx), which are later redeposited by rainfall. Nitrogen that runs off into watercourses or leaches into deeper soil layers is also considered [4]. Furthermore, potential soil organic carbon sequestration in natural pastures was integrated into the carbon footprint. The quantification of gases by source serves as a starting point for implementing farm-level mitigation strategies.

2. Materials and Methods

2.1. Study Characterization

In this case study, the analysis quantifies the CF of two contrasting Portuguese dairy farms: a conventional system (Farm A) and a pasture-based organic system (Farm B).

The CF was expressed using energy-corrected milk (ECM, production of energy-corrected milk) as the functional unit (1 kg of ECM). To consider the impact of the co-product, meat, we performed a system expansion. This methodology is particularly recommended when comparing organic and conventional systems [14], as organic farms are typically characterized by lower milk yields and higher meat outputs [15].

The boundaries of this study, represented in Figure 1, are limited from cradle to farm gate. This constitutes a partial life cycle assessment, considering emissions from extraction of raw materials to the gate of the farm. Emissions associated with the manufacture of machinery, medicines, pesticides and cleaning products were excluded, as they were deemed negligible [16]. The assessment includes the full year 2022, capturing seasonal variability.

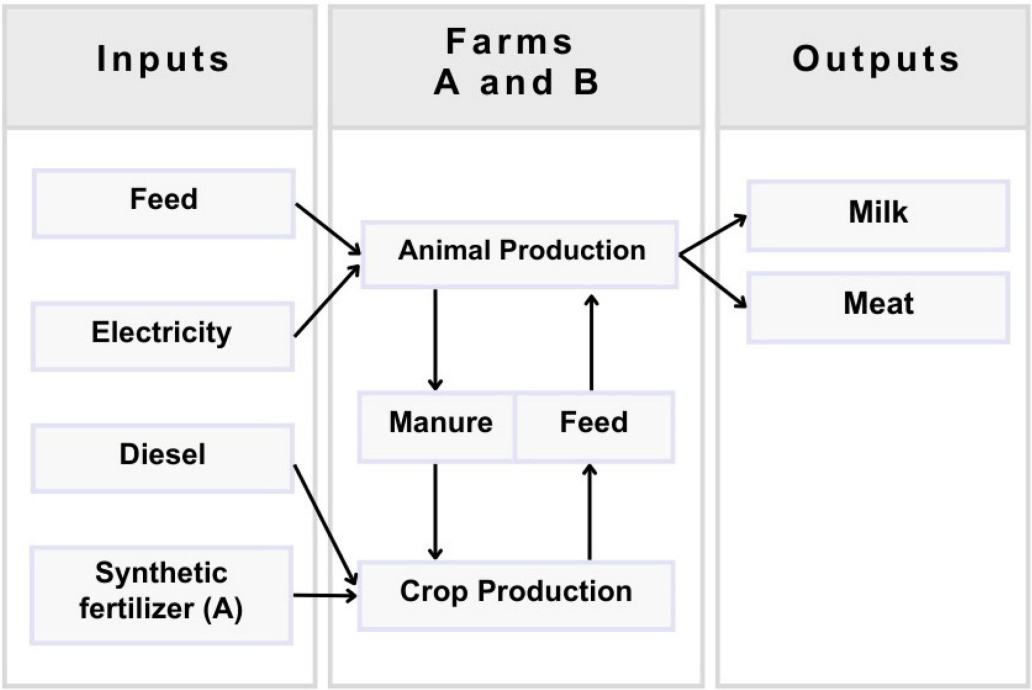

Figure 1. System boundaries used for this study in the two dairy farms.

2.2. Farm Description

2.2.1. Conventional Farm A

This farm, located in the vicinity of Lisbon, was selected for this study due to its conventional dairy cow production system. The herd is composed of Holstein–Friesian cows. Table 1 represents the number of animals in each group.

Table 1. Established animal groups for farm A.

Group	Number of Animals
Calves before weaning	40
Animals between 3 months and a year	120
Animals between 1 year and first lactation	177
Lactating cows, 1st lactation	91
Lactating cows after 2nd calving	219
Dry cows	19

Animals were milked twice daily. In the year considered, a lactating cow produced a mean of 36.86 kg of milk per day with 3.6% fat and 3.3% protein. Cows are housed all-year round, and lactating cows receive a mixture of maize silage, maize flour, brewer's yeast, soybean meal and grass silage. Additional information about the herd of Farm A can be found in Table S1.

Manure management in lactating cows housing utilizes a wave system. The excretions, along with sand bedding residues, are flushed out with water and pass through a structure where decantation occurs to separate the sand. Manure is then directed to a solid–liquid separator. The liquid part flows into a covered storage tank.

Liquid and solid manure are used to fertilize the farm's crops. Although 22 tons of manure were sold in 2022, for the purpose of calculating nitrous oxide emissions in the soil, it was assumed that all manure was used as crop fertilizer. Liquid manure is applied every six months, while the solid part is applied weekly.

2.2.2. Organic Farm B

This farm, located in Avis (district of Portalegre), has a total area of 1220 hectares. It has a large surface of Montado landscape, a silvopastoral landscape typical of the south of Portugal, combining pasture and cork oak trees. The area is divided into 3 farms. It manages organic dairy and beef cows.

On farm B, the dairy herd originated from crossbreeding Holstein–Friesian and Jersey breeds. Heifers are inseminated with sexed semen from Jersey bulls, while natural mating with Aberdeen Angus bulls is used in first- and multiple-lactation groups. Tables 2 and 3 represent the number of animals in each group.

Table 2. Established animal groups for dairy cows on farm B.

Groups (Milk Cows)	Number of Animals
Calves before weaning	91
Animals between 4 months and a year	29
Animals between 1 month and first lactation	124
Lactating cows, 1st lactation	103
Lactating cows after 2nd calving	396
Dry cows	119

Table 3. Established animal groups for beef cows on farm B.

Group (Beef Cows)	Number of Animals
Calves aged 0 to 6 months (0.4 LU)	87
Animals aged 6 months to 2 years (0.6 LU)	27
Animals older than 2 years	459

Dairy cows spend approximately 15 h per day at pasture. This schedule was considered for the whole year, as it is applied most of the time. Apart from the natural pasture, cows are fed with TMR (total mixed ration) when they are not at pasture. The TMR is made with grass silage produced on the farm and with distillers' grain, citrus pulp, brewer's yeast and spontaneous hay. Beef cows are permanently at pasture.

Cows were milked twice daily. For the year considered, a lactating cow produced an average of 12.9 kg of milk per day with 3.8% fat and 3.3% protein. Additional information about the herd of Farm B can be found in Table S1.

Regarding manure management in the housing facilities used partly during the day, the manure is dragged by a tractor and stored in a settling pond with a crust on the surface. Manure is used as fertilizer in the farm area at variable intervals, generally every 3 months for the solid fraction and every 6 months for the liquid fraction.

Grazing is managed adaptively with rotation of paddocks. This system is flexible and managed according to prevailing conditions. A large number of animals graze on a paddock for a short period before moving to another one, avoiding overgrazing and allowing sufficient time for pasture regeneration [17].

2.3. Data and Sample Collection

We collected data on these farms, including the type and number of animals, their type of feed, milk production, manure management systems, use of organic and inorganic fertilizers, electricity consumption, fossil fuels use, type and quantity of both on-farm and imported feed, and number and weight of sold carcasses.

To analyze the feed characteristics of farm B, we collected samples from the TMR on 5 different points of the manger. We also collected samples from the pasture. Both samples were analyzed in the laboratory of the Interprofessional Milk and Dairy Association through NIR (near-infrared spectroscopy). Regarding Farm A, NIR analysis of the feed already existed, from the same laboratory. We then proceeded to analyze the feeds of each group with the Software NASEM Dairy 8 (Nutrients Requirements of Dairy Cattle, 8th Revised Edition. V8 R2022.12.08). From this model's reports, it was possible to obtain an approximation of the energy values of feed, namely gross energy and digestible energy, and the daily intake and excretion of nitrogen by animals.

To analyze carbon dynamics in the soils of natural pastures at farm B, we used the RothC-26.3 model. This model required a soil sample from the farm, which was analyzed in the laboratory of the School of Agriculture of the University of Lisbon to determine soil granulometry. Additionally, chemical analysis data of the soil was provided, which included information on soil organic matter content, essential for performing the model.

2.4. Emission Estimation

Once all the farm data had been collected, values of ruminal methane and emissions from animal manure and soils were estimated using the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 10, "Emissions from Livestock and Manure Management", and 11, "N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application", were consulted. Following these guidelines,

the herd of each farm was divided into groups according to the type of animal, age and production. Tier 1 and 2 were used for the calculations.

The decrease in methane emissions caused by the solid–liquid separator is not accounted for in the IPCC guidelines. Therefore, we estimated the quantity of volatile solids in each fraction after separation, using the separation index 0.42 [18], as methane emissions are dependent on this value.

We also calculated the emissions from energy consumption on the farms using an emission factor of 2.690 kg of CO_2/liter of diesel [19]. Electricity emissions were also considered, and an emission factor of 0.309 CO_2/kWh was used [20].

For each imported feed, defined in this study as any feed originating outside the farm, an emission factor associated with its production was used from the databases AGRIBALYSE® 3.1.1, ECOALIM 8.1 and GFLI 2.0, the first of which also provides estimations for production of organic feed. For moist distiller's grains and molasses for farm B, conventional agriculture values were used instead of organic. The emission factors for brewer's yeast and citrus pulp were assumed to be zero, as these byproducts are not used for purposes other than ruminant feed. The emission factors for these imported feeds were, in these databases, calculated according to the economic allocation method, which is recommended by the IDF guidelines given the difficulty of attributing a physical allocation method [21].

Emissions from the production of synthetic fertilizers were also accounted for, as this is a process that requires a large amount of energy. We used the emission factors of 1.6 kg of CO_2-eq/kg of N for urea and 6.2 kg of CO_2-eq/kg of N for ammonium nitrate [22].

As previously mentioned, we performed a system expansion to account for meat production. After the estimation of the total CF of the farm, we subtracted the value of the emissions from meat production in an alternative production system [15]. The total amount of meat sold by the farm, obtained through the average carcass weight of each farm and the number of animals sold in the year of study, was multiplied by the average emission factor of the production of one kg of cow, according to the AGRIBALYSE databases. We used the emission factor of 11.8 kg of CO_2-eq/kg of meat for farm A, 17.5 kg of CO_2-eq/kg of meat for milk cows of farm B and 13.55 kg of CO_2-eq/kg of meat for beef cows of farm B; all of these values were obtained from the organic database.

Additional information about the the used emission factors can be found in Tables S2–S7.

2.5. Estimation of the Carbon Sequestration in Soils

To estimate the carbon sequestration in the soil of natural pastures of farm B we used the RothC-26.3 model, which seeks to predict soil organic carbon (SOC) dynamics in non-waterlogged surface soils. The model considers five different compartments—decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM)—and one inactive compartment, inert organic matter (IOM), resistant to decomposition. When adding carbon-rich materials, such as plant residues, roots and fertilizers, carbon is divided into DPM and RPM depending on soil type and land use. These compartments decompose and form BIO and HUM while releasing CO_2. The transformation into HUM + BIO or CO_2 depends on the percentage of clay in the soil. The decomposition rate is calculated on a monthly time step and is dependent on various factors, namely temperature, moisture and plant cover. To execute the model, parameters relating to environmental conditions in the municipality of Portalegre were collected, namely monthly precipitation and average air temperature in the year 2022. Since data on monthly evaporation were unknown, we used Müller's climate data on average monthly transpiration [23], as advised in the guidelines [24], and this result was divided by 0.75 [24] for monthly open-pan evaporation.

The clay content obtained from the analysis of the soil sample was 11.04%.

To estimate carbon additions to natural pastures, we used the equations and estimates of Morais et al. [25], relating to plant residues and excretions from grazing animals.

To calculate the carbon inputs from plant residues, we assumed an aboveground pasture productivity of 2.1 tons of dry matter (DM)/ha and a root-to-shoot ratio of 0.98. We also considered an animal intake of 0.61 kg of DM ingested per kg of DM pasture yield and a plant carbon fraction of 0.4 ton of C/ton of DM [25], [IPCC 2019]. For grazing manure, carbon inputs were calculated using a standard rate of 1.53 tons C/ha per livestock unit (LU), and a stocking rate of 2 LU/ha, reflecting the maximum allowance under organic farming regulations. Because this method relies on theoretical values in the literature for pasture productivity and intake rather than direct on-farm measurements, the final soil carbon estimates inherently carry some uncertainty.

The input parameters used to run the model are presented in Table 4.

Table 4. Needed inputs to create a scenario by the RothC model.

Environmental Conditions	Soil Management
Monthly rainfall (mm)	Monthly input of plant residues (t C/ha)
Monthly open pan evaporation (mm)	Monthly input of farmyard manure (t C/ha)
Average monthly mean air temperature (mm)	Soil cover (months)
Clay content of the soil (%)	
Depth of soil layer sampled (cm)	

To convert the percentage of organic matter in the soil (SOM) into total organic carbon (TOC), the SOM value was multiplied by 0.58 [25], which corresponds to the average fraction of carbon present in the organic matter and converted to tons of carbon per hectare.

The model was run to obtain carbon compartments in equilibrium with the TOC value. Climate values and soil carbon additions were run iteratively by the model until the equilibrium was reached [24].

3. Results and Discussion

3.1. Emissions of the Two Farms

Our calculations yielded a baseline carbon footprint of 1.43 kg of CO_2-eq/kg of ECM for conventional farm case A and 2.82 kg of CO_2-eq/kg of ECM for organic farm case B.

Because these figures represent the cases of two single farms operating under specific operational, dietary, and microclimatic conditions during 2022, they illustrate the performance of these specific facilities rather than system-wide averages for conventional versus organic dairy production in Portugal.

The contribution of each source of emission to the final CF can be observed in Table 5. The largest emission sources on farm A were imported feed (55%), ruminal fermentation (27%) and manure storage (14%). On farm B, the largest emission sources include ruminal methane (58%), imported feed (28%) and manure storage (15%).

Enteric methane is usually the largest emission source, often exceeding 50% of total emissions [2]. This aligns with farm B but contrasts with farm A, where it accounted for only 27% of emissions. In pasture systems, ruminal fermentation is the main contributor to the CF, while in other more intensive systems, emissions associated with feed production, manure management and fertilizer production are predominant [26].

Table 5. Contribution of each source of emission to the final CF of each farm.

Source—Gas	Conventional (A)		Organic (B)	
	kg CO_2eq/kg ECM	Fraction	kg CO_2eq/kg ECM	Fraction
Rumen—CH_4	0.39	0.27	1.63	0.58
Manure—CH_4	0.20	0.14	0.39	0.14
Manure—N_2O	0.06	0.04	0.02	0.01
Soils—N_2O	0.10	0.07	0.14	0.05
Diesel—CO_2	0.02	0.02	0.06	0.02
Electricity—CO_2	0.03	0.02	0.01	0.00
Imported feed—CO_2eq	0.79	0.55	0.79	0.28
Synthetic fertilizers—N_2O	0.02	0.01	0.00	0.00
Meat—CO_2eq	−0.16	−0.11	−0.22	−0.08
Total	1.43	1.00	2.82	1.00

Increasing animal productivity on farm B would reduce its carbon footprint, as CF in dairy systems is typically measured per kg of milk. Productivity can be enhanced in several ways such as reducing herd size by culling less productive animals, which leads to higher individual productivity and increased availability of pasture feed [27]. Pasture quality can also be improved, increasing the daily amount of nutrients ingested per animal. This shifts metabolism towards milk production instead of maintenance needs. A highly productive cow allocates a smaller fraction of its energy intake to maintenance requirements compared to a less productive cow [2]. These potential mitigation measures are derived from the literature and were not quantitively evaluated in the present study.

Because farm B operates an integrated system where dairy and beef herds share feed resources and labor, the beef section was included within the farm footprint. However, including the beef herd's meat credit primarily reflects total farm-level output rather than dairy efficiency alone. Although this present study employed system expansion, IDF guidelines recommend the physical allocation method. Applying physical allocation would have increased the final carbon footprint of the milk, as it partitions existing farm emissions rather than subtracting avoided emissions from beef production. This distinction should be considered when comparing our results with other studies.

The addition of carbon sequestration in natural pastures in the CF of organic farm B reduced it to 2.06 kg of CO_2-eq/kg of ECM. It is recommended to present this value separately, since the inclusion of sequestration in the soil can significantly vary the CF [21]. The CF was thus reduced by 27% with the inclusion of sequestration in its natural pastures.

3.2. Ruminal Fermentation

Methane from enteric fermentation was the second-largest emission source on farm A and the largest on farm B. Methane emission values, factors on which it is dependent, and feed efficiency are compiled in Table 6.

Table 6. Parameters relating to ruminal methane emissions for a lactating cow in both farms.

Farm	Daily Emission per Animal (kg CH_4/day)	DMI (kg)	DE (%)	MY (g CH_4/ kg DMI)	FE (kg ECM/ kg DMI)
A	0.42	22.0	72.4	19.0	1.70
B (milk cows)	0.27	12.8	52.0	21.4	0.99

DMI, dry matter intake; DE, digestible energy; MY, methane yield; FE, feed efficiency.

A lactating cow on farm A emitted 152.6 kg of CH_4 per year (0.42 kg of CH_4 per day), contrasting with farm B, in which a lactating cow emitted 99.9 kg of CH_4 per year (0.27 kg of CH_4 per day).

Ruminal methane emissions are multifactorial and depend on parameters such as dry matter intake, the weight of the animal, its milk production, fat percentage and the type of farming system [28].

Calculation of ruminal methane included the parameter dry matter intake (DMI), which was considerably higher on farm A (22.0 kg) compared to B (12.7 kg). This disparity primarily stems from differences in animal genetics and weight, the first being a Holstein–Friesian cow with an average of 780 kg of weight, and the second being the result of a crossing between Jersey and Holstein, with an average of 470 kg, which largely varies the amount of ingested feed and thus the amount of methane produced. DMI can also have been limited on farm B due to the reduced amount of forage in pastures, intensified by the periods of drought in the year of study, together with the low-quality forage with a lower digestibility [29].

There may be uncertainties arising from the data collection process relating to feeding of the animals, since on farm A, these data were previously provided, while on farm B, we collected samples and DMI was subsequently estimated from IPCC equations [4]. On this farm, we collected samples from the pasture, and although these were collected in five different points, they may have been unrepresentative of the total pasture area of the farm, as it occupies a large area and has a high forage diversity. Additionally, although beef cattle are permanently on pasture, their diets can be supplemented according to the season and existing conditions, such as drought, and an exact quantity of this supplementation has not been provided. It is important to note that 2022 was characterized by severe drought across this region. While the Alentejo typically experiences very hot and dry summers, the abnormal precipitation deficit in 2022 reduced natural pasture yields, forcing farm B to purchase an increased volume of off-farm feed. Consequently, this likely inflated the carbon footprint associated with external feed production.

Enteric emissions per unit of output were substantially higher for farm B (1.63 kg of CO_2-eq/ECM) than farm A (0.39 CO_2-eq/ECM), with emissions on farm A being 76% lower than on farm B. In similar studies [16,28], emissions (kg of CO_2-eq/ECM) of ruminal methane of cows at pasture and in confined systems were also compared. Although these studies have also found higher emissions for pasture-based animals, the emissions in confined systems were only 24% lower compared to pasture-based systems in the study of de Léis and 18% lower in the study of Flysjö. The contrast with our study can be explained by the much lower milk production in B compared to A.

In the study of Uddin et al. [30], a comparison was made between the CF of farms with the Holstein–Friesian breed and farms with the Jersey breed, reaching values of enteric methane of 0.63 kg of CO_2-eq/kg FPCM for the Holstein–Friesian breed and of 0.68 kg of CO_2-eq/kg FPCM for the Jersey breed. Although, in this article, the value is also lower for the Friesian breed, the difference between the two breeds is once again considerably lower than the difference between farm A and B.

Although the amount of enteric methane produced per cow is lower on farm B, the result in kg of CO_2-eq/kg of ECM is notably lower on farm A. This could be due to the amount of milk produced, since total production on farm A is more than double the production on farm B with a smaller number of productive animals, which reinforces the importance of productivity in reducing emissions per kg of milk. The high emission on farm B can also be due to the high level of non-productive animals. As observed in the previous paragraphs, the low productivity of farm B made it difficult to compare its emissions with those recorded in the literature, as the results are systematically presented per kg of milk.

Feed efficiency (FE) was, in this study, defined as milk yield per kg of DMI [14] and was considerably higher on farm A (1.70 kg ECM/kg of DMI) compared to B (0.99 kg ECM/kg of DMI).

The higher FE observed on farm A (1.70 kg ECM/kg of DMI) could be due to the predominance of maize silage in the feed, which has considerably higher digestibility and less predominance of more fibrous forage [31] as is the case of farm B (0.99 kg ECM/kg of DMI). This, combined once again with the much higher productivity on farm A, leads to a lower proportion of nutrients used in maintenance functions, resulting in their dilution [2]. The quality of the forage also has an important role in reducing the amount of enteric methane emitted by animals [32].

3.3. Manure Management: Methane Emissions

For farm A, methane emissions from manure storage were 0.20 kg of CO_2-eq/ECM, while for farm B they were 0.39 kg of CO_2-eq/ECM. Tables 7 and 8 represent, for each subgroup of farm A and the dairy cows of farm B, the methane emission values from manure storage and the influencing parameters.

Table 7. Methane emission from manure storage, in each group of farm A, and parameters on which it is dependent.

Group	Daily Emission (kg CH_4/day)	VS (kg DM/day)	Type of System	Retention Time	MCF (%)
<1 year	0.10	1.95	Deep bedding	>1 month	41.0
1–2 years	0.12	2.40	Deep bedding	>1 month	41.0
1st lactation	0.17	2.61 3.61	Solid Liquid	Regularly 6 months	4.0 41.0
Lactation after 2nd calving	0.17	2.61 3.61	Solid Liquid	Regularly 6 months	4.0 41.0
Dry cows	0.01	2.91	Solid	Regularly	4.0

VS, volatile solids; MCF, methane conversion factor.

Table 8. Methane emission from manure storage, in each group of dairy cows on farm B, and parameters on which it is dependent.

Group	Daily Emission (kg CH_4/day)	VS (kg DM/day)	Type of System	Retention Time	MCF (%)
<1 year	0.002	2.79	Pasture	/	0.5
1-year lactation	0.003	4.58	Pasture	/	0.5
1st lactation	0.121	5.54	Settling pond Pasture	6 months /	41.0 0.5
Lactation after 2nd calving	0.121	5.54	Settling pond Pasture	6 months /	41.0 0.5
Dry cows	0.084	3.75	Settling pond Pasture	6 months /	41.0 0.5

On farm A, a lactating cow emitted 0.17 kg of CH_4 per day from manure storage, amounting to 62.6 kg of CH_4 annually. On farm B, a lactating dairy cow emitted 0.12 kg of CH_4 per day, or 44.5 kg of CH_4 per year.

During manure storage, emissions are affected by oxygen availability, volatile solid quantity, temperature and storage duration [33]. These characteristics can make the emis-

sions from this source vary from negligible to highest on the farm. The methane conversion factor (MCF) was a key parameter for these calculations and was dependent on the type of system and temperature. The farms are in a region with a temperate climate (annual temperature between 15 and 25 °C), with emissions varying depending on the season. The difference in emissions between winter and summer is 75%, according to the review of Jayasundara for Canada [34], and only from 10 °C on does a significant methane emission occur.

On farm A, the <1 year and the 1–2 years groups are maintained in a deep bedding system, where manure accumulates over the months. The methane conversion factor used was 41.0% [4], and it resulted in an estimated emission of 0.10 and 0.12 kg of CH_4 per animal per day, respectively, or 35.2 and 43.9 kg of CH_4 per year. For lactating cows, the emissions presented were the result of the sum of manure stored after separation of solids and liquids. The MCF used for manure stored in liquid form with a retention time of 6 months was 41.0%, and in solid form, it was 4.0% [4].

For farm B, the highest emissions occurred when animals were confined. During this period, manure is stored in a settling pond, with a retention time of 6 months, which is almost entirely responsible for the value of methane from manure of these animals. For lactating animals, it was estimated that 44.5 kg of CH_4 was emitted per animal per year or 0.12 kg of CH_4 per day. In contrast, for animals that spent all their time grazing, such as the 1 year-to-lactation group, only 1.0 kg of CH_4 per year or 0.003 kg of CH_4 was emitted per animal per day. For the settling pond, a value of MCF of 41.0% was used, while for grazing animals, we used an MCF of 0.47% [4].

Systems such as liquid tanks and settling ponds, in which manure is treated as a liquid, are assigned higher MCF values due to the anaerobic environment, which promotes ideal conditions for the production of methane. The extended storage time on such farms leads to the growth of active methanogenic populations, typically requiring around five months at a temperature of 15 °C [35]. Emissions can be reduced by decreasing manure storage duration. Particularly during warmer seasons, it is recommended to store manure for less than 150 days, through frequent application to the soil [35].

On farm A, the use of solid–liquid separation for lactating cows significantly reduces methane emissions from the liquid fraction, through reduction of the amount of volatile solids [36]. Without this separation, system methane emissions from a lactating cow on farm A would have been 109.2 kg of CH_4 per year as opposed to the estimated 62.6 kg of CH_4 (this value accounts for both liquid and solid fractions). When comparing methane emissions from manure of lactating cows on farm A with the ones of B (during the hours in which animals are confined), emissions are lower on farm A. This reduction is partly due to the solid–liquid separation system for farm A.

On farms where manure is managed in liquid form, it is possible to establish a system that captures methane produced during anaerobic digestion, allowing it to be used as renewable energy on the farm. This can be done by associating the solid–liquid separator with an anaerobic digester. Implementing this system on farms already managing manure in liquid form is relatively straightforward and offers other advantages such as odor control and reduction of pathogens [34].

Farm A keeps some of the animals in a deep bedding system, which leads to emissions comparable to the methane emissions of the liquid systems.

During pasture hours, methane emissions of farm B were almost negligible, since the amount of emitted methane is minimal when manure is directly excreted on pasture [4].

3.4. Manure Management: Nitrous Oxide Emissions

For this source, 0.05 kg of CO_2-eq/ECM were emitted on farm A and 0.02 kg of CO_2-eq/ECM were emitted on farm B.

Nitrous oxide emissions depend on both total excreted nitrogen and system-specific emission factors. Tables 9 and 10 have compiled, for each group of farm A and dairy cows of farm B, the emissions of N_2O from manure storage, the type of system and used emission factors.

Combining direct and indirect emissions, the total N_2O emissions for a lactating cow on farm A was 0.0036 kg of N_2O per day or 1.32 kg of N_2O per year. On farm B, for lactating cows during the period that they were not at pasture, the emission was 0.0005 kg of N_2O per day or 0.18 kg of N_2O per year.

Table 9. N_2O emissions for varying conditions on farm A.

Groups	Nex (kg/day)	Type of System	Direct Emissions		Indirect Emissions	
			EF_3 (kg N_2O -N/kg N)	Total d. (kg N_2O/day)	Volatilized Fraction	Total i. (kg N_2O/day)
<1 year	0.19	Deep bedding	0.010	0.003	0.25	0.0007
1–2 years	0.18	Deep bedding	0.010	0.003	0.25	0.0007
1st lactation	0.41	Liquid + cover	0.005	0.003	0.10	0.0006
Lactation after 2nd birth	0.41	Liquid + cover	0.005	0.003	0.10	0.0006
Dry cows	0.20	Solid	0.010	0.003	0.30	0.0009

Nex, daily N excretion per animal; EF_3, emission factor for direct emissions; total d., total direct N_2O emissions per day; volatilized fraction, fraction of volatilized N to NH_3 and NOx; total i., total indirect N_2O emissions per day.

Table 10. N_2O emissions for varying conditions on farm B.

Groups	Nex (kg/day)	Type of System	Direct Emissions		Indirect Emissions	
			EF_3 (kg N_2O -N/kg N)	Total d. (kg N_2O/day)	Volatilized Fraction	Total i. (kg N_2O/day)
<1 year	0.07	Pasture	/	/	/	/
1-year lactation	0.14	Pasture	/	/	/	/
1st lactation	0.12	Settling pond + crust	0.005	0.0003	0.30	0.0002
Lactation after 2nd birth	0.12	Settling pond + crust	0.005	0.0003	0.30	0.0002
Dry cows	0.14	Settling pond + crust	0.005	0.0005	0.30	0.0002

Lower N_2O emissions on farm B are due to the large number of hours these animals spend at pasture, which reduces the amount of manure in the settling pond [4]. On farm A, the highest emission factors were used for the deep bedding system and the solid storage, namely 0.01 kg of N_2O/kg excreted of N. Nitrous oxide emissions occur when aerobic and anaerobic conditions exist in close proximity [37], which typically occurs in solid systems. The literature differs regarding emission factors of N_2O. Emissions vary depending on the oxygenation conditions of the deep bedding system and solid storage. In consequence, the values used may have associated uncertainty.

For farm A, the emission factor of 0.005 kg of N_2O-N/kg of N excreted was considered for the covered liquid system, and the same value was used for the slurry system with a crust of farm B. In a liquid system, where anaerobic conditions prevail, N_2O emissions are considered negligible. However, the formation of a crust by the solid particles of manure creates an aerobic environment in the crust, promoting the nitrification reaction [37].

Similarly, by covering the system with a permeable cover, it is possible for microorganisms to colonize it, creating both aerobic and anaerobic areas [34]. Therefore, this same emission factor value was considered for both farms.

Ammonia (NH_3) volatilization in manure management systems accounts for important N losses, which can lead to indirect N_2O emissions after deposition [4]. Contrary to direct emissions, covering liquid systems leads to a decrease in NH_3 emissions, diminishing indirect N_2O production. A volatilized fraction of 0.30 was used for the liquid system with crust for farm B, and 0.10 was used for the liquid system with cover for farm A, while the value for a liquid system without cover would be 0.48 [4]. Thus, the cover acts as mitigation measure for NH_3 volatilization [34], as it reduced exposure to wind [36].

3.5. Soils: Nitrous Oxide Emissions

The N sources used to calculate soil emissions included livestock manure applied as fertilizer on both farms, synthetic fertilizers used on farm A, and N from grazing animal excretions on farm B. The total amount of nitrogen applied to soils on farm A was 55,341 kg of N from manure and 10,452 kg of N from synthetic fertilizers. For farm B, 12,261 kg of N was applied from manure storage and 23,614 kg of N was excreted by grazing animals. Total emissions of direct and indirect nitrous oxide were 1508 kg of N_2O per year, or 411,556 kg of CO_2-eq, for farm A and 969 kg of N_2O per year, or 264,555 kg of CO_2-eq, for dairy cows on farm B. Emissions from this source were therefore lower on farm B.

Figures 2 and 3 represent for both farms the quantities of added nitrogen by different sources and the consequent nitrous oxide emissions.

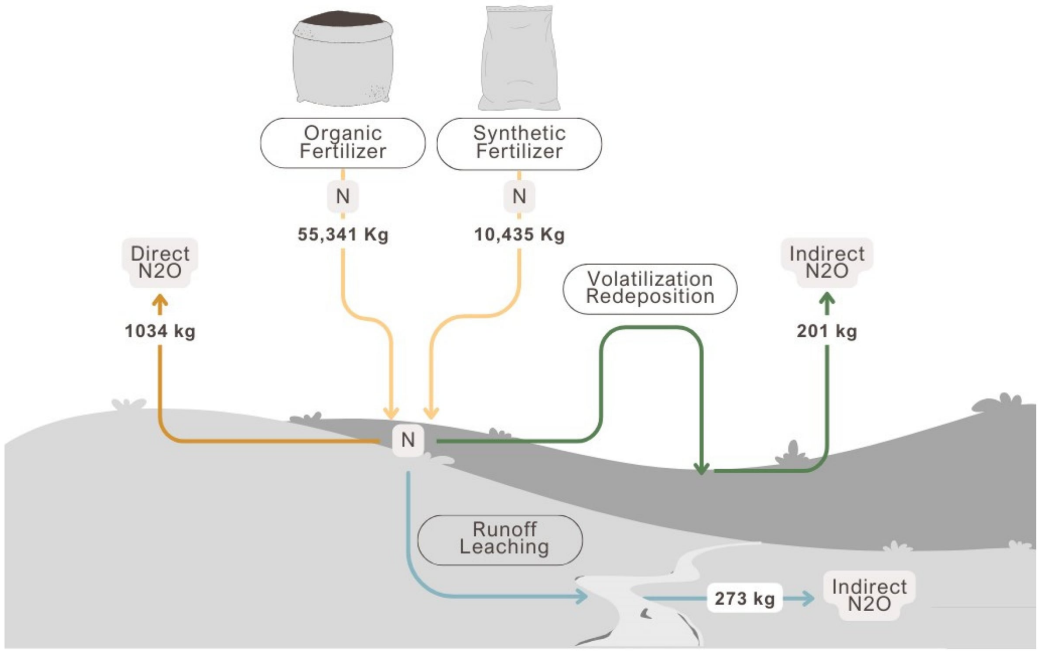

Figure 2. Nitrogen added to the soil, and direct and indirect nitrous oxide emissions, for fields of farm A. Yellow arrow, nitrogen added to the soil; orange arrow, direct N_2O emission; green arrow, indirect N_2O emission after volatilization of NH_3 and NOx; blue arrow, indirect N_2O emission after leaching of nitrogen.

The total nitrogen applied to the soils on farm A was 55,341 kg from manure and 10,452 kg from synthetic fertilizers. On farm B, 12,261 kg of nitrogen came from manure storage and 23,614 kg were excreted by grazing animals. The total direct and indirect N_2O emissions were 1508 kg of N_2O per year, equivalent to 411,556 kg of CO_2-eq for farm A, and 969 kg of N_2O per year, or 264,555 kg of CO_2-eq, for dairy cows on farm B. As a result,

emissions from this source were lower on farm B. Figures 2 and 3 show the quantities of nitrogen added from different sources and the resulting N_2O emissions for both farms.

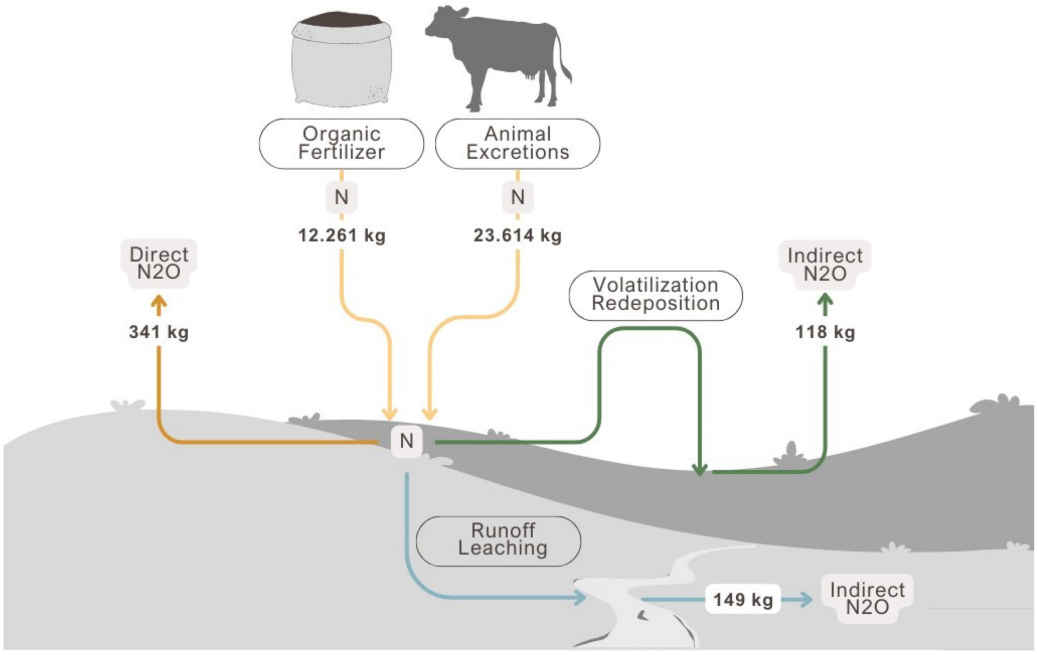

Figure 3. Nitrogen added to the soil, and direct and indirect nitrous oxide emissions, for fields of farm B.

IPCC guidelines for calculating manure emissions from manure management are considered a simplified model, where only the quantity of added N is accounted for. These guidelines do not consider the complex processes nor prevalent conditions involved in the production of N_2O, which leads to a high variability in emissions [16]. Parameters such as type of manure [37], which varies depending on treatment, or type of soil, with higher emissions in arable terrains compared to pasture, are not considered [38]. The same emission factor was always considered, of 0.010 kg of N_2O-N/kg of N for emissions of organic and inorganic fertilizers and 0.004 kg of N_2O-N/kg of N for feces and urine excreted by animals on pasture. The guidelines indicate a large uncertainty range of these values. According to Flysjö [16], methods such as the ones used in the IPCC, with fixed values for emissions factors of N_2O, are overly simplistic when it comes to quantifying these kinds of complex biological processes.

3.6. Emissions from Imported Feed

Annual emissions from imported feed for farm A were 3,321,327 kg of CO_2-eq, or 4308 kg of CO_2-eq per animal, and for farm B, they were 1,464,275 kg of CO_2-eq or 1106 kg of CO_2-eq per animal. Around 7473 kg of feed was annually imported per animal on farm A, and around 2479 kg was imported on farm B. Tables 11 and 12 representrepresent a compilation of the imported feed in the two farms, together with the emission factor used to calculate the footprint of their production.

Farm A produces part of the feed supplied to the animals, the largest fraction being imported. The feedstuff with the highest emission factor was soybean meal. On farm B, the animals feed directly on pastures for part of the day. When confined, they receive TMR with feed produced on the farm, supplemented with imported components. Most of the feed imported onto this farm has a lower emission factor than the feed imported on farm A.

Table 11. Inventory of imported feed and emission factors for farm A.

Imported Feed		Quantity (kg/year)	FE (kg CO_2eq) and Source
Maize silage		1,891,330	0.20; Ecoalim
Brewer's yeast		1,281,880	0.00
Maize grain		789,349	0.48; Ecoalim
Citrus pulp		629,260	0.00
Soybean meal		473,452	2.45; GFLI
Straw		334,760	0.70; Ecoalim
Mixture 1	Soybean hulls	190,207	0.76; GFLI
	Barley flour	83,167	0.70; GFLI
	Palmitic acid	26,251	3.80; GFLI
	Bicarbonate	25,119	1.19; Base Carbone
	Calcium carbonate	23,875	0.08; Ecoalim
	Fat	13,012	3.80; Ecoalim

FE, emission factor; source, database used.

Table 12. Inventory of imported feed and emission factors for farm B.

Imported Feed	Quantity (kg/year)	FE (kg CO_2eq) and Source
Tomato pomace	1,216,300	0.20; Agribalyse
Brewer's grains	1,025,660	0.89; Ecoalim (conventional)
Vicia	254,520	0.39; Agribalyse
Alfafa	242,860	0.25; Agribalyse
Maize silage	133,480	0.18; Agribalyse
Grass silage	127,350	0.30; Agribalyse
Ryegrass silage	95,980	0.30; Agribalyse
Wheat	83,230	0.35; Agribalyse
Barley	53,832	0.42; Agribalyse
Molasses	49,400	0.11; Ecoalim (conventional)

As expected, because it uses a pasture-based system, farm B imported less feed per animal than farm A. However, we expected lower emissions from this source. Hietala et al. [39] estimated the CF of six biological European farms with animals who had access to pasture. In this study, emissions associated with imported feed accounted for 3% of total emissions, which is significantly lower than the emission of farm B (28%). This high value can be explained by the dependence of this farm on feed import, due to the lack of quantity and quality of feed in the pastures, which intensified with a severe drought in this region in the year 2022. The emission factors used for this study may also have influenced this result.

Compared to the imported feed value of the farm in the study of Gross et al. [14] before its conversion to organic farming (0.41 kg of CO_2-eq/kg of ECM and 35% of total emissions), the emission value of imported feed for farm A was significantly higher (0.79 kg

of CO_2-eq/kg of ECM and 55% of total emissions). This could be because farm A produces less feed on the farm and relies more on imported feed, with higher emission factors.

Brazilian states with the highest emission factor for soy production are typically those where deforestation and land conversion for agriculture have occurred more recently. This is because the emissions associated with these land-use changes are still included in current emission calculations [40]. Additionally, in conventional farming systems, a significant portion of emissions from feed production can be attributed to the extensive use of synthetic fertilizers and fossil fuels. These emissions are particularly high when they do not have increased crop yields [32].

On farm A, replacing feed with high emission factors such as soymeal with others with a lower CF and produced locally could significantly reduce emissions. One way to encourage the purchase of local products with a lower environmental impact could be through the implementation of incentives from national or European organizations, making such products more appealing to producers. However, when substituting one ingredient for another, even if they have similar nutritional characteristics, adjustments to the proportions of other ingredients in the feed are also necessary. It is important to assess the full CF which comes from this change, not just the emissions factor of the specific ingredient being replaced [32]. It is also noted that the complexity of feed composition—driven by factors such as costs, regional feed availability, climate, and farming practices—makes it challenging to create general recommendations for reducing the CF at farm level.

For farm A, we considered in the emission factor of maize and soybean meal its production and transportation to Europe. However, road transportation to the farm for these and other feeds produced in national territory were not accounted for, which we considered an uncertainty factor.

3.7. Carbon Sequestration in Soils

The estimated carbon sequestration in the soils of natural pastures of farm B was 1.59 tons C/ha for the year 2022. When considering 800 ha of natural pasture, the total sequestration was around 1272 tons of C.

Table 13 represents the carbon additions to the soil and total value of sequestered carbon.

Table 13. Sequestered C by natural pastures of farm B.

Final SOC (t C/ha)	Plant Residues (t C/ha)	Manure (t C/ha)	Sequestered C (t C/ha)
17.38	1.08	3.06	1.59

Final SOC, measured total organic carbon; plant residues and manure, estimation of annual added carbon to the soil from plant residues and animal manure; sequestered C, sequestered C between January and December 2022 by the model.

The soil carbon sequestration value of farm B was presented separately from the total carbon footprint. Since there is currently no consensus on integrating carbon sequestration into life cycle assessments, and since most similar studies have excluded it, presenting this value separately provides greater transparency and enables better comparison with other published results.

Accurately estimating carbon sequestration is challenging due to the variability in climate, soil properties and management practices [33]. The results of the simulation conducted for this study may not be representative of the entire farm, which has a large pasture area. Additionally, we used soil carbon inputs derived from values in the literature for pasture productivity, which is dependent on numerous factors.

To evaluate the impact of this theoretical assumption, we performed a sensitivity analysis on plant carbon inputs. We assumed an input of 1.08 t C/ha coming from plant residues, resulting in a total carbon sequestration of 1.59 t C/ha. As RothC uses first-order decomposition rates for its carbon inputs, changing the amount of plant residues leads to a proportional change in the calculated sequestration. Considering the potential broad variability of the rainfed pasture within the Montado system, where aboveground biomass production can easily fluctuate between rainier and drier years, we assumed a variability of ±20% in pasture productivity and grazing intake. Assuming −20% in carbon input from this source, total sequestered carbon would decrease to 1.51 t C/ha according to the RothC model. On the other hand, an increase of 20% would have resulted in a total sequestered carbon value of 1.67 t C/ha. These variations demonstrate that although plant carbon inputs influence the final carbon footprint, their impact on total carbon sequestration remains relatively minor (±0.08 t C/ha).

Other variables such as climate factors (monthly rainfall, average air temperature, and open-pan evaporation) apply nonlinear effects on soil decomposition rates in RothC. As 2022 was a dry year in this region, these climatic parameters introduce additional uncertainty. The estimated value therefore carries a high degree of uncertainty, representing a limitation of this theoretical modeling approach. The interpretation of this farm's carbon footprint together with the carbon sequestration value must account for these uncertainties. Although it has not been evaluated in the present study, conducting a sensitivity analysis of other RothC parameters is a recommended step for future studies to better understand the weight of these theoretical assumptions.

The value of 1.59 ton of C/ha stored on this farm's pastures is within the carbon sequestration range for permanent pastures in Ireland, the United Kingdom and the United States, of 0.79 to 1.79 ton of C/ha annually, and above the average of 1.19 ton of C/ha for the same countries [41]. With the large pasture area associated with the holistic practices, with high animal density, short duration of grazing and long period of regeneration of parcels, a positive sequestration value was expected.

An important limitation of this study is that carbon sequestration was quantified exclusively for the permanent pastures of farm B. Cropland areas from both farms (maize on farm A and sorghum on farm B) were not assessed due to insufficient data. This boundary constraint affects the net comparison between the two systems differently. Farm A uses conventional agricultural practices in its maize fields, which typically induce soil organic carbon loss through tillage. Conversely, farm B uses regenerative agriculture practices in its sorghum fields, such as cover crops and no-till farming, which tend to increase soil organic carbon content. Consequently, excluding croplands spares farm A from accounting for tillage-induced emissions, while underestimating the total sequestration potential of farm B. We recommend its estimation in future studies.

3.8. Limitations and Uncertainty of the Assessment

The final carbon footprints obtained in this study are single point estimates. Due to several characteristics of the available data, no quantitative uncertainty assessment (e.g., Monte Carlo simulation) was performed. We acknowledge this as a limitation of the study.

Firstly, the inventory for each farm is based on a single year of data (2022), with only one farm per studied system. There were no repeated observations from which empirical distribution could be derived for data such as dry matter intake, feed composition or manure management.

Secondly, the emission factors for imported feed were taken from databases (AGRIBALYSE® 3.1.1, ECOALIM 8.1 and GFLI 2.0), which are presented as single values, and consistent uncertainty distributions were not available.

Moreover, enteric and manure methane and soil nitrous oxide emissions were calculated with IPCC Tier 1 and 2 methodologies. The emission factors are associated with a wide uncertainty range at the scale of national inventories.

Soil carbon sequestration was estimated with a single deterministic simulation with RothC. For influential inputs other than plant carbon input, such as climatic factors, no assessment has been made. The uncertainty of the sequestration estimate is therefore larger than the range reported in Section 3.7.

In conclusion, the results should be interpreted as estimates for the two farms in the studied year and not as values with defined confidence intervals. The difference between the two farms is large (1.43 vs. 2.82 kg of CO_2-eq/kg of ECM), but its robustness was not tested, and this should be assessed in future studies.

4. Conclusions

This study estimated the greenhouse gas emissions of one conventional and one organic dairy farm in Portugal. Data collection and calculations were challenging because of the differences between the two production systems. The carbon footprint (CF) was 1.43 kg of CO_2-eq/kg of energy-corrected milk (ECM) on the conventional farm and 2.82 kg of CO_2-eq/kg of ECM on the organic farm. Both values are higher than those reported in the literature. When carbon sequestration in pastures was included, the organic farm's CF fell to 2.06 kg of CO_2-eq/kg of ECM. On the conventional farm, feed imports were the largest emission source, whereas on the organic farm, enteric fermentation dominated.

Because the study rests on a two-farm case design, these results describe the two farms studied and should not be taken as representative of conventional and organic production in general. Larger samples across multiple farms and regions would be needed to draw broader conclusions.

Nonetheless, the case study provides a useful starting point for identifying mitigation measures on the two farms analyzed and on similar setups. On the conventional farm, animal productivity appears to play an important role in reducing the CF when expressed per kg of milk, while on the organic farm, carbon sequestration in pastures had a substantial effect on the final value.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture16232602/s1, Table S1: Herd Characterization; Table S2: Enteric Methane Calculation; Table S3: Manure Management System: Methane Parameters; Table S4: Nitrous Oxide Emissions from Manure; Table S5: Soil Nitrogen Inputs and Nitrous Oxide Emissions; Table S6: Emissions from production of synthetic fertilizers; Table S7: Emissions from co-product "meat"; Table S8: Summary of emissions for Farm A; Table S9: Summary of Emissions for Farm B.

Author Contributions: Conceptualization, L.P. and R.B.; methodology, L.P.; software, M.Y.O. and Nuno Gaspar; formal analysis, M.Y.O. and N.G.; investigation, I.P. and L.P.; resources, R.B. and N.G.; writing—original draft preparation, L.P.; writing—review and editing, R.B., N.G. and I.P.; visualization, L.P.; supervision, R.B. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The farm-level data used in this study were obtained from two farms and cannot be publicly shared due to confidentiality and privacy considerations. Further inquiries can be directed to the corresponding author(s). The data supporting the emission calculations, including

the emission factors used in the carbon footprint assessment, are derived from publicly available databases, which are cited in the manuscript.

Conflicts of Interest: Author Nuno Gaspar was employed by the company Serbuvet. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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